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WEATHER CONDITIONS AND FOREST FIRES IN CALIFORNIA

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CONTENTS

	Page
The problem	1
Summary of previous investigations	2
Forest Service investigations	2
Weather Bureau investigations	5
Data employed in present study	5
Relative humidity	6
Evaporation	8
The wind factor	11
Fire data	14
Regional influence of humidity and wind velocity on spread of fire	14
Limitations in the use of evaporation as a measure of fire conditions	20
Summary	21
Literature cited	23

THE PROBLEM

The relation between weather and forest fires that is of most pressing importance to foresters in the western United States appears in the occasional occurrence of unusually dangerous days or periods, generally spoken of as "blow-up days." These frequently produce greater burned-over area, damage, and suppression cost than the remaining 95 per cent of the fire season. In some instances they are more destructive and costly than several entire seasons.

Particularly in the white pine region of Idaho and Montana, and to a lesser extent in the Douglas fir region of Washington and Oregon, experience has shown that consistent protection involves capable handling of fires in these periods, which may occur in their worst form only two or three times in a decade.

In California the tendency of foresters to attribute success or failure of fire protection in a particular year to weather conditions has been much less pronounced than in the Pacific Northwest. However, there is no doubt that fire protection in California faces, though to a lesser degree, the same problem that is of such outstanding importance in the Northwest.

In each of the fire seasons from 1920 to 1923, inclusive, there has occurred in California a period of critical weather conditions during

which fire has swept over a high percentage of the total area burned during the season. As shown in Table 1, these periods have been as short as 4 days and as long as 28 days.

Because of the great importance of the problem to foresters, several independent studies have been initiated by the Forest Service in the important forest regions, aiming to supplement the work of the United States Weather Bureau. These have attempted both to define the general term "fire weather" and to determine the principal climatic causes of sudden changes in the inflammability of forest fuels. In measuring the results of fire weather some foresters have used number of fires; others have employed relative rate of spread of fire and area burned; others have emphasized primarily the difficulty of fire control.

TABLE 1.—*Concentration of burned area in critical periods*

Year	Period of "blow-up" days	Areas burned			
		Total for season	Normal days	"Blow-up" days	
		Acres	*Acres*	*Acres*	*Per cent*
1920	July 22 to Aug. 18	156, 160	24, 720	131, 440	84
1921	July 2 to 17	59, 940	37, 390	22, 550	38
1922	Sept. 8 to 18	136, 200	45, 110	91, 090	67
1923	Sept. 16 to 19	55, 496	24, 747	30, 749	55

The pioneer work of the Weather Bureau left little question that relative humidity and wind velocity are the principal climatic elements responsible for fluctuations in fire weather. Naturally enough in the experimental work different investigators emphasized the importance of one or the other of these in different ways and employed different bases, as well as various instrumental methods, for predicting fire weather. This very diversity of attack, in spite of some tendency toward confusion and apparent contradiction, has covered the field of feasible methods more rapidly than at first appeared possible.

There are several important questions remaining to be studied for California conditions, which may be listed as follows:

1. What weather factor or factors best express fire danger, particularly the occasional very critical periods?
2. What instrumental method or methods best measure fire danger?
3. Do simultaneous fluctuations in weather conditions take place over large areas, or is the problem of fire weather prediction essentially a local one?

SUMMARY OF PREVIOUS INVESTIGATIONS

Before consideration of the California data it will be profitable to summarize the more important conclusions of earlier investigators both in California and elsewhere in the West.

FOREST SERVICE INVESTIGATIONS

One of the earliest investigations of the factors influencing the spread of fire was conducted at the Feather River Forest Experi-

ment Station in California from 1915 to 1917. The study was based on carefully observed experimental fires, which were purposely set and which burned under known conditions in the open (*11*).[1] The most important result of this investigation was that within the scope of the conditions encountered rate of spread varied as the second power of the wind velocity; that is, doubling the velocity of the wind quadrupled the spread of fire. Wind was thus clearly designated as a factor of great importance in the spread of fire. No decisive answer to the influence of other factors was obtained at this time, because of the difficulty of isolating and controlling such influences as relative humidity and temperature.

This investigation was probably the earliest to demonstrate the fundamentally important fact that the litter of the forest floor has the capacity of absorbing moisture from the air independently of that received from precipitation. Although only one kind of fuel was examined—coniferous needles—it was found that during the night, when humidity was relatively high, the moisture content of the fuel was decidedly higher than in the preceding afternoon. This quality of forest fuel explains the influence on inflammability of variations in relative humidity. In this study, an attempt was made to define the inflammability point of litter, on the basis of the percentage of moisture contained; that is, the degree of moisture that would permit spread of fire starting from a match. A tentative figure of 8 per cent for this particular fuel was established. It was shown that during a normal summer season the moisture content of the litter exceeded 8 per cent on north slopes a large part of the time, but rarely on south slopes.

At about the same time Larsen conducted a statistical survey of Idaho and Montana, seeking to correlate the fire history of the region with the major meteorological factors (*8*). His investigation served to show clearly the great complexity of the problem. The major conclusions were that the fire history of a period was dependent not only on the weather conditions during the time the fire burned, but also on the length of the preceding drought, the prevalence of hot and dry weather, the intensity of the wind, etc. He did not attempt to specify any one or two factors as the controlling influences in the spread of fire, neither did he attempt to suggest methods of forecasting critical weather conditions. He was probably the first investigator to recognize that low relative humidity is a factor of great importance in periods of extreme fire danger, though he did not specify this as the only important consideration. Much of his investigation was devoted to the analysis of the general character of fire seasons; and it was found that—(1) the character of the winter precipitation and snowfall has no perceptible influence upon the subsequent fire season, and (2) the distribution and amount of spring and summer precipitation directly affects the number and size of fires during the season. His studies also indicated that the combination of spring and summer precipitation, average relative humidity, and wind movement affected the periods within a fire season. He recognized the major importance of the physiographic regions on both the character of forests and the character of climate.

[1] Reference is made by number (italic) to "Literature cited," p. 23.

Later, Osborne and Hofmann (*7*) working in Oregon and Washington attacked the problem from two angles. An analysis of the weather conditions occurring at the time of some of the great historic fires indicated that relative humidity was the element of dominant importance, since it was found that very low humidity had always occurred at the time of extraordinary spread of fires. Further detailed investigations in the Douglas fir region itself emphasized this conclusion. These investigators have stated that "extreme fire hazards are always a result of low relative humidity." Osborne and Hofmann have done considerable work in forecasting the occurrence of low relative humidity and have used this factor also in selecting methods of suppression of going fires. They have analyzed the hygroscopic qualities of a wide range of forest fuels, particularly of finely divided, moisture-sensitive fuels, such as moss and fireweed, and have shown that these flash fuels respond more readily and to a greater extent to changes in relative humidity than do compact layers of litter. Their analyses have confirmed previous studies as to the hygroscopic nature of forest fuels.

These investigators have proposed a definite scale for the relation of relative humidity and forest-fire hazard in the Pacific Northwest and have stated that with more than 60 per cent relative humidity, even without rain, fires will not spread, while with 25 per cent or less relative humidity crown fires will develop.

Munns (*9*), working in California in 1921, developed the hypothesis that fluctations in fire hazard were simultaneous with fluctuations in evaporation. His studies, based on the records of the Converse Forest Experiment Station in southern California, led him to conclude that evaporation integrated the three principal factors of wind, relative humidity, and temperature, and therefore more nearly reflected fire conditions than a study of any one of the factors alone. An important conclusion in the study was that practically simultaneous fluctuations in fire weather conditions took place over almost the entire State. Munns, like other investigators, found unmistakably that the occurrence of unusual fire hazard was associated with dry east and north winds. He did not attempt, however, to determine whether low humidity or wind velocity or the combination of the two was the operative factor in the spread of fire. Munns concluded that the periodic fluctuations in evaporation were so regular that fire weather could be predicted from a study of the course of day-to-day evaporation, and that vapor pressure could be used directly as a reasonably reliable indicator of fire hazard.

Munns subsequently employed data obtained in the analysis of the fire history of California forests in an attempt to correlate the occurrence of good and bad fire seasons with the periods of maximum and minimum sun-spot numbers and to predict the general character of fire seasons from sun-spot numbers as a basis.

Gisborne, working in the Northern Rocky Mountain region with Dunlap, of the Forest Products Laboratory, has determined the moisture content of various forest fuels when they are in a state of equilibrium with different air temperatures and humidities. An instrument, a duff hygrometer, has been developed which reads directly the moisture content of litter in place on the forest floor.

Using the data on existing moisture content in connection with regional forecasts of the Weather Bureau (*5*), Gisborne has attempted short-term predictions of the future moisture content, or inflammability, of forest materials.

Gisborne finds (*6*) that a considerable range exists in the relation of moisture content to degree of inflammability. Using these data and the information available concerning the lag of moisture content of fuels behind the changes in atmospheric conditions, he has essayed to translate the regional predictions of the Weather Bureau into terms of probable inflammability for specific localities for the ensuing 36 hours. For the season of 1924 his predictions are asserted to have been about 85 per cent successful.

Using data over a period of years in California, the writers (*12*) have attempted to give some expression to the relative rate of spread of fires in what are generally spoken of as good and bad seasons by determining the percentage of fires in a given homogeneous group that, when attacked within a fixed length of time after starting, exceed 10 acres. This method of analysis shows considerable fluctuations in rate of spread as between seasons, especially for a region such as California, where the climatic factors apparently have less dominant influence on fire hazard than in the Northwest.

WEATHER BUREAU INVESTIGATIONS

The meteorologists of the Weather Bureau have contributed extensively to the literature of weather and fire. Williams (*3*), Beals (*2*), Palmer (*10*), and Alexander (*1*) have dealt chiefly with the question of generalized prediction of fire weather, leaving to foresters the field of determining what constitutes fire weather for any particular region or forest type. The earliest writers on the subject assumed without argument that humidity and winds were the principal factors controlling the spread of fires. As long ago as 1913 the Weather Bureau began its fire-weather warning service on the Pacific coast, and this has continued up to the present.

The fire-weather warnings of the bureau for California are based solely on the study of the daily weather map and are regional in character. The only special data that have been purposely obtained for this service are telegraphic dispatches from selected forest lookout stations, notifying of change of direction and velocity of the wind. In the view of professional forecasters, the changes in relative humidity, in wind direction and velocity, and in temperature are but expressions of the fundamentally important changes in pressure distribution which form their major basis for forecasts. With the facilities at their command local forecasts are impossible, although it is recognized by many meteorologists that these are not only desirable but necessary, because of the local variations in a region the size of California.

DATA EMPLOYED IN THE PRESENT STUDY

In analyzing the relation of weather and fire in the following brief form attention is necessarily confined to the data for California, and all conclusions apply to that State only. A check, however, will

be attempted with the tentative conclusions arrived at in other regions. The material used comprises: (1) The Weather Bureau records of relative humidity and wind velocity at Red Bluff, Sacramento, Fresno, Independence, and Los Angeles, Calif., and Reno, Nev.; (2) records of evaporation obtained on the different national forests; (3) data on fires taken from the individual fire reports; and (4) data on wind velocity and wind direction obtained on various lookout peaks on the national forests.

RELATIVE HUMIDITY

In analyzing the relative humidity data an average figure for each day of the fire season was determined by averaging the 5 a. m., noon, and 5 p. m. readings. The data for each station were then plotted. The material is so voluminous that full presentation is impracticable here, and the record for one typical season is included. (Fig. 1.) In comparing the records from the three principal California valley stations—Sacramento, Red Bluff, and Fresno—for the period 1920 to 1923 it was found that:

(1) Up and down fluctuations in relative humidity, especially major peaks and depressions, generally coincide with the tendency of Fresno to lag a day or so behind the more northerly stations.

(2) The lowest depressions at Red Bluff and Sacramento coincide, but are not always present at Fresno in such pronounced form.

(3) Some strong depressions at Red Bluff are absent at Sacramento; for example, August 18, 1920.

(4) General seasonal trends are about the same at all stations.

It is impossible to predict from humidity data what its trend will be on the following day; it is simply a guess.

The principal conclusion in regard to relative humidity is that the major fluctuations are practically simultaneous throughout the entire Great Valley of California (see table 2); and if it is true that the adjacent mountain regions are affected by the same fluctuations, then it can be concluded that the major part of the State is in one climatic province. This is of course in harmony with the findings of meteorologists. It is further probable that extreme conditions of low humidity are greatest in the northern part of the State and tend to decrease toward the south, so that sudden changes in fire conditions are likely to be more serious in the northern forests.

The relative humidity data for Reno and Independence show that these two stations, both lying east of the Sierra Nevada divide, are very similar to each other in the occurrence of peaks and troughs. However, neither of them shows consistent relations with the California valley stations. Certain peaks and depressions are conspicuous at all five stations, while others are present at Reno and Independence but absent at the other stations.

In so far as the region under discussion is concerned, any one of the three valley stations (Red Bluff, Sacramento, or Fresno) may fairly be used as a base station against which to compare fire data, provided the major fluctuations found in the valley exist also in the adjacent mountain region.

FIG. 1.—The striking features of these three curves are the great difference between high and low points of relative humidity, the tendency toward a wave form of curve, and, most important, the concurrence of the conspicuous high and low points at the three widely separated stations

TABLE 2.—*Principal days of low humidity at valley stations of Weather Bureau*[1]

Year and month	Days of month as recorded at different stations			Year and month	Days of month as recorded at different stations		
	Red Bluff	Sacramento	Fresno		Red Bluff	Sacramento	Fresno
1920				1922			
June	19–20	19–20	20	June	17–18	17	17–20
Do	24	24	25	Do	23	23–26	24–27
July	6–7	5–7	7–11	July	1–2	2	5–6
Do		23		Do	15–16	15	15–17
Do	22–31	31	20–31	Do	19	19	22–23
August	1–18	1–16	1, 7	Do	27–30	27, 30	27
Do			3–18	August	6–7	6–7	7
Do	30–31	31	31	Do			16–18
September	2	2	2–4	Do	25	26	26–27
Do	10–11	10–11	10–12	September	3	1–2	1–2
Do	16	16	16–17	Do	8–10	10	8–9
Do	22	22	22	Do		15–16	17–18
Do	26–29	28–29	25–29	Do			
1921				1923			
June	21–22	21–22	22–23	June	11–13	11–13	11–13
Do	26	26–27	26	Do		27–30	27–30
July	2–3	2–3	2–10	July	1		1
Do	4–16	4		Do	5		6
Do	21–22	21	22–24	Do	12		12–13
August	5	4, 5	5–6	Do	21	21	21
Do	15	15	16	Do	26–28	26–28	31
Do	20	19		August	6–8	6–8	7
Do	29–30	29	22–30	Do	14–15	14–15	14–15
September	7–9	4	6	Do	25–26	25–26	25–27
Do	15	15	14, 16	Do	31		31
Do	20–21	20–21	22, 24	September	1–9	3–9	1–13
Do	29	29	28	Do	16–17	16–17	17

[1] The table shows clearly how closely the low humidity dates correspond for the stations, particularly very low points such as July 2–3, 1921, Sept. 8–10, 1922, and Sept. 16–17 1923.

EVAPORATION

Following Munns's study (*9*), systematic collection of evaporation data was begun in the California region, and in 1921 a porous-cup atmometer was installed in each of the 15 important national forests. The following year the Bates atmometer was also installed at 5 stations, as a check on the other type. The instruments were maintained through the season of 1923.

In spite of many faulty records,[2] a mass of reliable observations remains, of which only a representative sample can be included here. Analysis of these records, partially represented in Figure 2, leads to the following conclusions:

(1) Major peaks and troughs are present at all stations and generally coincide in time.

(2) Where day-to-day fluctuations in evaporation are small, with no sustained trend either up or down, there is no consistent relation even between near-by stations.

[2] The porous-cup atmometer, developed at Johns Hopkins University by B. E. Livingston, clogs easily and then fails to register. It is very susceptible to breakage, and also requires a supply of distilled water difficult to maintain at isolated stations in the national forests. The Bates atmometer, produced by Carlos G. Bates, of the Rocky Mountain Forest Experiment Station, is an instrument of great durability and hence superior in many respects to the porous cup; but considerable instrumental errors have developed in its use, and no two Bates atmometers run side by side give identical results. As is shown in Figure 3, from the standpoint of instrumentation the Bates and the porous-cup instruments give very similar records when run side by side and when both are in good condition. It also appears that the Bates instrument gives reasonably good records under conditions when the porous cup is practically useless. But even at the best, the two instruments do not maintain a constant working ratio.

(3) Although at any particular station evaporation tends to rise, then to fall, then to rise again in a more or less rhythmic fashion, it is practically a "50–50" guess on any particular day whether the succeeding day will show a higher or lower evaporation.

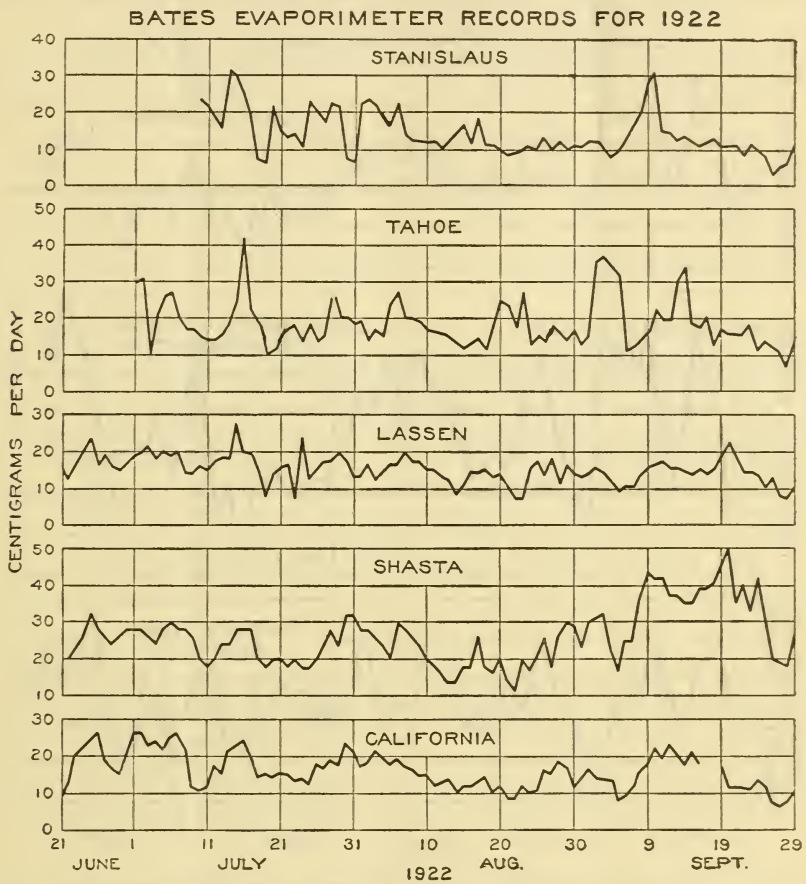

FIG. 2.—Evaporation, like relative humidity, fluctuates widely, with a tendency toward wavelike periods. At the national forest stations here shown the principal high and low points generally coincide, indicating that the entire group of national forests of California is in one climatic province

During each season at practically all stations there come times when the day-to-day fluctuations are relatively small, with no continued trend in one direction, and when the graph of evaporation

presents a saw-tooth appearance rather than a true peak-and-valley aspect. It seems reasonably certain that for the California region the day-to-day fluctuations of evaporation, like those of relative humidity, can not be satisfactorily predicted from the study of these records alone. Both are obviously but one expression of major

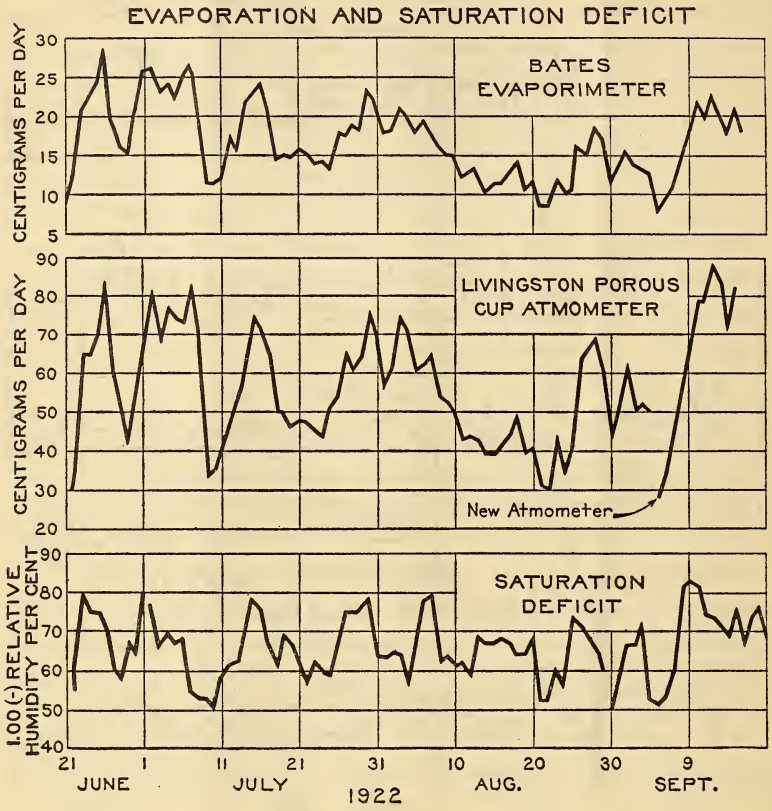

FIG. 3.—A comparison of evaporation data from Bates and porous-cup instruments at one station in the California National Forest exhibits a close correspondence. Saturation deficit (or 100 minus relative humidity) at Red Bluff is traced for comparison with evaporation. The indication here is that relative humidity is the principal though not the sole factor in evaporation

climatic fluctuations leading back to variations in barometric pressure.

By plotting saturation deficit—that is, one minus relative humidity—and evaporation, curves of the same general form are obtained, so that the two factors of relative humidity and evaporation can

be compared directly. It is found that in a general way evaporation in the mountains fluctuates in much the same direction and to about the same degree as relative humidity in the valleys. (Fig. 3.) This is particularly true of the principal peaks and troughs; when neither humidity nor evaporation shows a consistent trend, a comparison of the two shows no positive relation whatever. It is evident in comparing evaporation with relative humidity and wind velocity that while wind velocity has some effect on evaporation it is principally relative humidity that determines the course of the evaporation curve.

THE WIND FACTOR

Wind velocity as a factor in the spread of fire is altogether too important to be overlooked. Wind is so obvious in its effects and so readily discernable that it is universally recognized by fire fighters as a principal agent in spreading fires and affecting the methods of control.

The information available for an analysis of the wind factor consists principally of anemometer records on 12 primary lookouts well distributed throughout the entire area of the pine region, and in addition the data obtained by the Weather Bureau at its major stations located in the Great Valley of California. Figure 4 shows the lookout records for the season 1917. In detail no correlation appears among the stations nor even between near-by stations, such as between Mount Eddy and Grizzly Peak which are some 25 miles apart in air line. However, one conclusion can be stated without qualification: Days of unusually high wind movement, for example, September 10 and 21, 1917, are common to nearly all mountain peaks. These particular days, it is worth noting, are those on which north and east winds prevail.

Turning to the Weather Bureau records of the valley stations at Red Bluff, Sacramento, and Fresno (fig. 5), the first impression on examining the wind velocity is that no obvious correlation whatever exists among the different stations. As in the case of the lookout peaks, however, there is one conspicuous exception to this general statement: Days showing the maximum wind velocity for the entire season are simultaneous at Red Bluff and Sacramento and are generally but not always present at Fresno as well. July 2 and 3, 1921; September 8 and 9, 1922; and September 16 and 17, 1923, are the outstanding examples; the first of these only is shown on Figure 5.

The records for the mountain stations for these seasons are not included here, but it was found in analyzing them that the same dates have conspicuously high wind velocities in the mountains as in the valleys. The dates of conspicuously high wind movement at valley stations are likewise those of north and east winds and therefore of exceptionally low relative humidity.

In attempting to analyze the wind factor in its effect on the rate of spread of fire, by far the most important point is the rôle of exceptional winds. In this respect it is evident that the entire national forest region of the Sierras and northern Coast Range can be treated as a unit because of the simultaneous occurrence of high winds throughout the region.

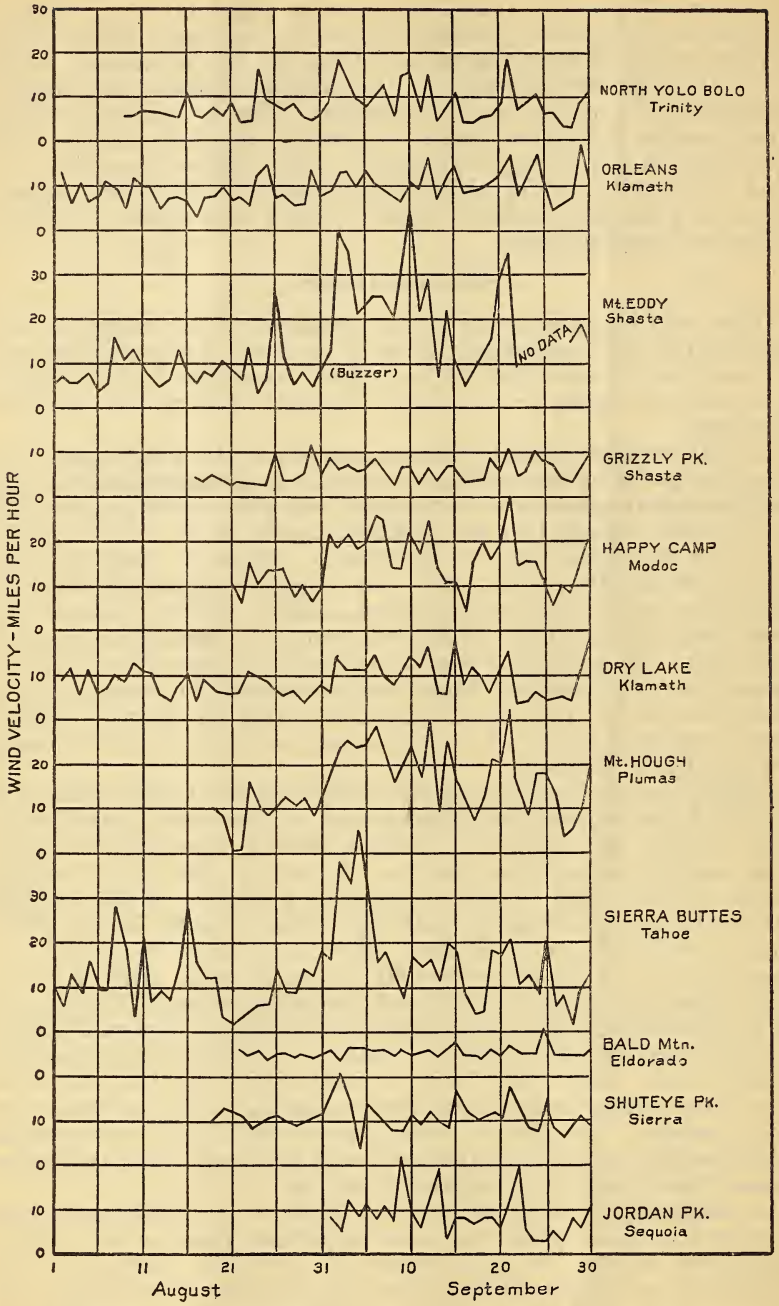

FIG. 4. Wind velocities taken on the principal mountain tops in California national forests in 1917 by anemometer records reveal striking similarities in only a few instances, chiefly when very high winds occurred. September 21 is a particularly clear case

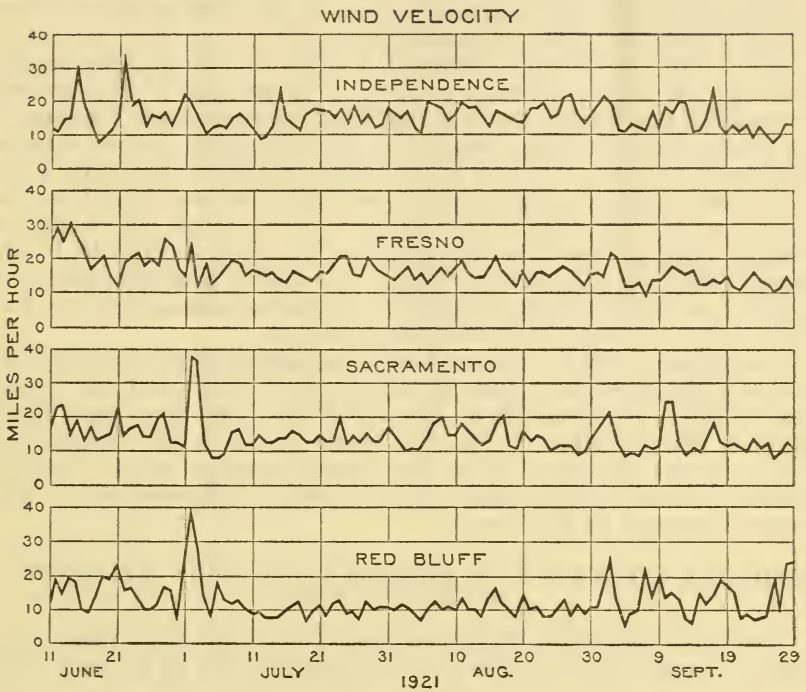

FIG. 5.—Average maximum daily wind-velocity records from the principal valley stations agree with the records from mountain tops (fig. 4) in showing that high points are concurrent at the several stations only on days of conspicuously heavy winds, as on July 2 and 3

FIRE DATA

For the years 1920, 1921, 1922, a tabulation was made showing for each national forest for each day from June 11 to September 30 (the generally recognized fire season) the number of A, B, and C fires[3] separately, and the acreage burned; then for each day the fire data were totaled, showing the total number of fires, total acres burned, percentage of C fires, and size of the average fire. A total of 2,495 fires was used in this analysis.

Fires were necessarily allocated to days on which they started, although of course a certain number of large class C fires actually burned for periods of varying length. Consequently a fire starting on a day of low wind movement and high humidity, but not attacked effectively for two or three days, would in some cases show a considerable acreage burned, in the event that before control was attained relative humidity had become low or wind movement had become high. Therefore the data in the table shortly to be discussed, showing different variations of relative humidity and wind velocity, are not to be regarded as exact mathematical indices of the rate of spread under these two major factors.

One other possible source of error in this method of analysis is the average speed of attack in suppression; that is, if the fires in one group were reached in an average time of one hour and those in another group in two hours, the latter group, other things being equal, would certainly show the larger average area. However, partial check of the fire data indicates that no compensation is necessary on account of this factor.

REGIONAL INFLUENCE OF HUMIDITY AND WIND VELOCITY ON SPREAD OF FIRE

For the California region, excluding the southern part of the State, it seems true that the principal fluctuations in weather conditions are generally simultaneous over a large area. This is particularly true of the days or periods of exceptionally low humidity and high winds, which are of course simply the expressions of well-known types of pressure distribution.

An attempt has been made to separate the wind factor from the other major factor, relative humidity. For this purpose the Weather Bureau data at Red Bluff have been used and days and periods of different relative humidity have been taken as the primary basis of subdivision; that is, periods of less than 25 per cent average daily humidity, those with 26 to 30 per cent, with 31 to 35 per cent, etc., have been treated as units; then, within each of these classes, a further subdivision has been made on the basis of the daily maximum wind velocity. Days or periods of less than 10 miles per hour, 11 to 20 miles, and over 20 miles have been segregated and each class treated as a unit.

The results, as shown in Table 3, make it clear that, with relative humidity constant, the size of the average fire is greatly influenced by the velocity of the wind, particularly when the relative humidity is below 40 per cent. When the humidity is below 25 per cent an

[3] Class A fires are those covering less than one-quarter acre; class B range from one-quarter to 10 acres; class C are over 10 acres in size.

average fire of 57 acres spreads to 487 acres with an increase in wind velocity. In another humidity series the same average fire area is increased twelvefold by high winds. Nor is this confined to periods of low relative humidity, for with humidity above 40 per cent a similar progression in size of average fire accompanies increasing wind velocity, though to a less striking degree. In a general way this effect of wind velocity conforms to the conclusions reached in the detailed study of experimental fires at the Feather River Station, as already cited.

TABLE 3.—*Effect of relative humidity and wind velocity on size of fires*

[Red Bluff as base station for 3-year period]

Relative humidity (per cent)	Average fire areas in three wind-velocity periods			Average all fires	Percentage of days with over 20 miles velocity of wind
	Less than 10 miles per hour	1 to 20 miles per hour	21 miles per hour and over		
	Acres	*Acres*	*Acres*	*Acres*	*Per cent*
20 to 25	57	314	487	292	16
26 to 30	80	244	----------	218	6
31 to 35	57	31	663	47	5
36 to 40	16	81	420	76	4
41 to 45	19	27	80	21	[1] 16
46 to 50	12	40	----------	36	2
51 to 55	11	82	80	78	13

[1] 60 per cent of the days with 41 to 45 per cent relative humidity and over 20 miles wind-velocity showed no fire hazard.

Considering Table 3 from the other angle, namely, as showing changes due to relative humidity while wind velocity remains constant, it is equally apparent that increases in humidity result in decreased size of the average fire. Within the range of humidity actually found during a fire season, the size of the average fire with minimum humidity is about five or six times as great as with maximum humidity. Remembering that the values of this table are only indicative values, it seems fair to assert that wind and relative humidity in the California pine region are of about equal weight in affecting spread of fire. Within the range of the data it seems to be true that days or periods of low humidity and low wind velocity are no more dangerous than days of high humidity and high wind velocity. At the very least, wind velocity is a major factor in controlling the spread of fire, and relative humidity alone, important though it is, does not tell the whole story. The data are shown graphically in figure 6.

A significant feature should be noted in the last column of Table 3. With each relative-humidity group the percentage of days of high-wind velocity (over 20 miles per hour) was figured, and it was found that high winds are relatively more frequent with very low and with very high relative humidity than with the intermediate values. From the standpoint of organized fire protection, obviously the most critical combination of factors is in the coincidence of very low relative humidity and very high wind. The previous discussion of the Weather Bureau data has indicated definitely that seasonal

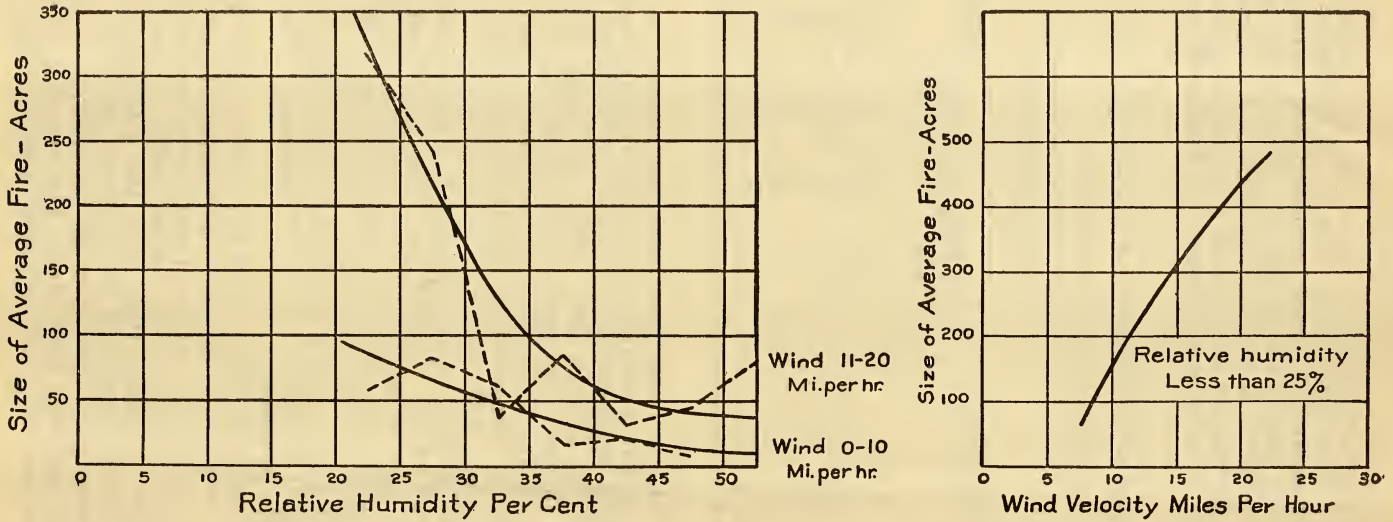

FIG. 6.—The relation of relative humidity and wind velocity to spread of fires. The left-hand figure shows that, with wind velocity remaining the same, relative humidity is an exceedingly important factor in controlling average size of fires; and that the lower the humidity is, the greater the average size of fires. The right-hand figure shows that with relative humidity constant (at 20 to 25 per cent) there is a similar increase in size of fire as the wind velocity increases

maxima of wind velocity generally coincide in point of time with seasonable minima of relative humidity. That this combination of factors, which for the past four years has occurred but once a season, results in a very high percentage of the total burned area (see Table 1) has already been indicated. The data for three of these years are shown in somewhat different fashion in Table 4.

TABLE 4.—*Relation of atmospheric humidity to number of fires*

Year	Periods of high humidity			Periods of low humidity		
	Number of fires	C fires	Fires per day	Total fires	C fires	Fires per day
	No.	*Per cent*	*No.*	*No.*	*Per cent*	*No.*
1920	446	15	8.0	575	29	10.5
1921	481	17	6.4	262	19	7.1
1922	516	19	7.0	215	23	6.1
Total	1,443	17	7.0	1,052	24	7.9

Aside from the year 1920, in which a very heavy lightning storm occurred within a low-humidity period, the average number of fires per day has not varied greatly between low and high humidity periods. Humidity alone is of no significance in this region as an indicator of occurrence of fires, although both the number and percentage of C fires, good indicators of rate of spread, are greater during periods of low humidity.

All of these data, it should be emphasized, are to be regarded as approximations of the regional influence of relative humidity and wind velocity. From the standpoint of regional prediction they at least serve to show clearly the principal problem—the concurrence of low humidity and high-wind velocity. Any attempt to state that a specified humidity will or will not of itself result in a break or "blow-up" is not justified by the study. This is clearly indicated in Figure 7. In general, days of fires of large average size in 1923 coincide with days of low humidity; yet on August 25 and 26, for example, although low humidity prevailed, fires were held to a small average size. The importance of the combination of low humidity and high wind is clearly indicated on September 16 and 17.

Perhaps the best opportunity for studying the influence of either extreme high-wind velocity or extreme low relative humidity is to be found in the early-season and late-season fires that are by no means uncommon. One particularly noteworthy example is illustrated in Figure 8. In this case the fire season had presumably been over for considerably more than a month, when suddenly disastrous crown fires developed in second-growth stands, chiefly outside the national forests and originating from "light burning" fires which had been set for the usual purposes of that practice. Examination of the weather data shows that on the days of those fires relative humidity was no lower than it had been in the previous week, but that wind velocity suddenly jumped from a maximum of 10 and 15 miles an hour to 40 or 50 miles per hour. The sudden outbreak of the fires was evidently a result of the exceptional wind velocity. Heavy rains had preceded this period and consequently the soil and

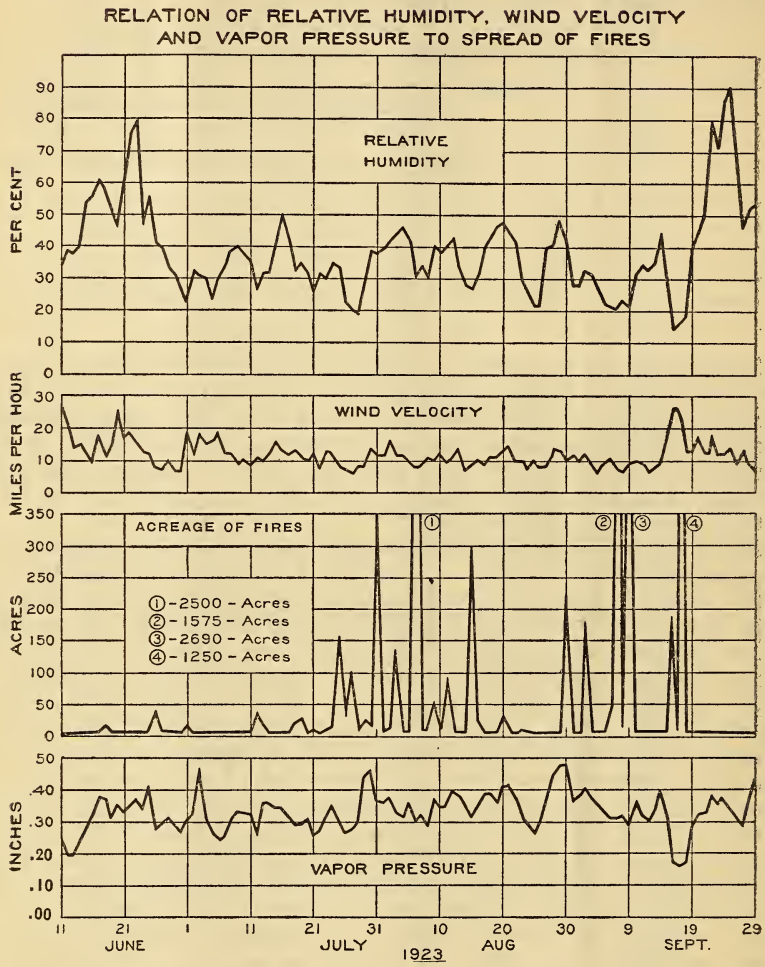

Fig. 7.—The fire peaks are found usually when relative humidity is at or near a low point. The effect of a sustained low is shown by the three large fires between August 30 and September 18. High wind velocity, as on September 16 and 17, is evidently an important control of rate of spread of fire. Weather data from Red Bluff; vapor pressure based on 3 determinations daily

litter were moist. It is improbable that low humidity alone could have produced a similar flare-up, as on November 20, six days before the crown fires developed and when light fires were actually burning but wind velocity was low, the humidity had reached as low a point as on the fire days.

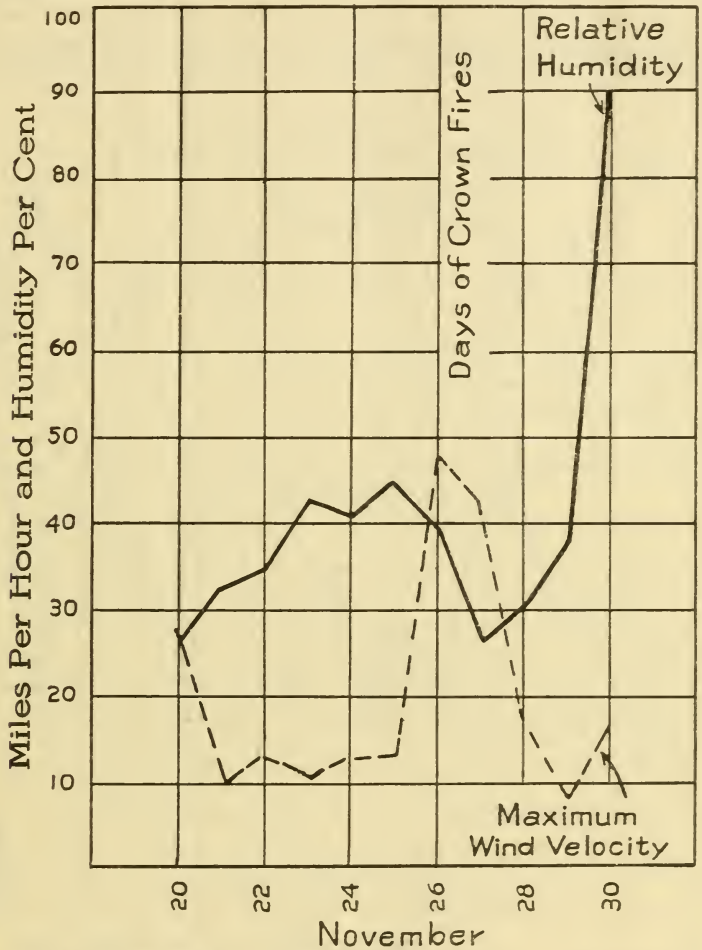

FIG. 8.—Relation of relative humidity and wind velocity to late-season fires. The data plotted are from Sacramento Weather Bureau records for 1919 and are employed to illustrate a striking concurrence of low relative humidity and high wind velocity, occurring after the usual fire season. This combination of circumstances permitted crown fires to develop November 26–28, although a few days earlier, with low humidity and low wind velocity, the fires remained simply creeping surface fires. Figures at left express percentage of relative humidity and also wind velocity in miles per hour

The outbreak cited is not an unusual occurrence. In slash-disposal work on the national forests, unless great care is exercised, sudden winds may cause the rapid spread of fires even when the burning of the slash piles is started after soaking rains or a fall of snow.

LIMITATIONS IN THE USE OF EVAPORATION AS A MEASURE OF FIRE CONDITIONS

Bigelow's investigations on the laws governing evaporation from a water surface (*4*) prove conclusively that the wind factor in the formula is a function of the first power of the rate of wind. The investigations on the rate of spread of fires, previously cited, show that in this respect wind is very much more important, and that its

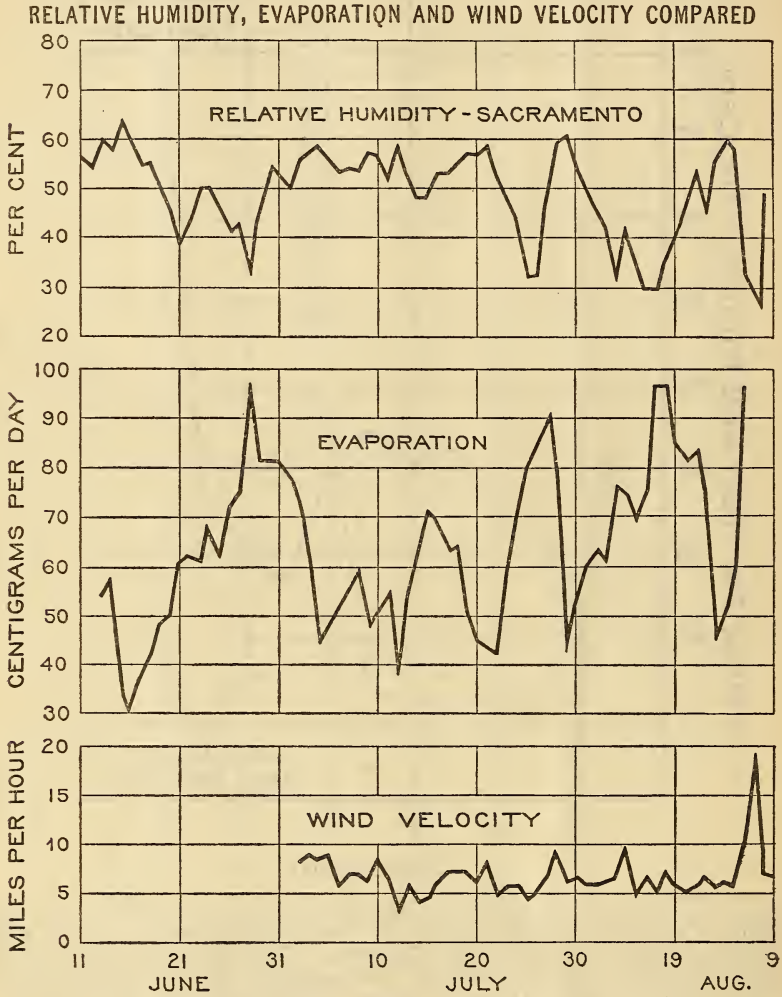

FIG. 9.—Evaporation in the mountains reflects closely the course of relative humidity in the valley. High points of humidity correspond to low points of evaporation. Evaporation does not reflect wind movement alone

place in the rate-of-spread formula must be expressed as a function of the second power. It is to be doubted whether the instrumental differences in measuring the evaporation from a free water surface and from the porous-cup or Bates instruments are sufficient to absorb any such difference in the wind factor. It therefore appears very probable that the atmometer is fundamentally incapable of giving proper weight to one of the two principal factors affecting spread of fires (fig. 9).

Comparing further the evaporation and the humidity records, it is found that days of equal evaporation may be either days of low relative humidity and low wind movement, or days of high relative humidity and high wind movement. Whether or not such days are of equal importance so far as fires are concerned is at least open to question. The evaporation records generally do not show as high peaks in September as in June, although the fire history demonstrates conclusively that the September periods are incomparably worse than those earlier in the year. The investigations of evaporation from water surface have shown conclusively the importance of sunshine in the evaporations formulæ; and this may be the factor that is operative in our records since obviously the number of hours of sunshine per day is considerably less in September than in June. At any rate, it is by no means proved that evaporation is anything more than a general indicator of fire hazard.

However, it is undoubtedly true that within a short period, when evaporation is increasing, fire hazard likewise is increasing, but not necessarily in the same ratio in which the evaporation changes. If a longer record is considered, as for an entire fire season, it does not follow at all that days of equal evaporation represent days of equal fire hazard. In general, it may be fairly said of evaporation records that the days of highest evaporation do not always correspond to the days of greatest fire hazard. In many of the records, although days of great fire hazard correspond to peaks of evaporation, these peaks are not necessarily the highest of the season.

It was believed originally that it would be possible to establish absolute rates of evaporation as indicating different degrees of fire hazard. An examination of the data at hand does not permit any such distinction to be made. Some of the highest absolute rates are attained at points of considerable elevation and relatively low rates at points in the foothill and lower forest region. The value of the evaporation data would seem to lie purely in the direction and general elevation of the curve. Any fine-drawn attempts to establish a mathematical basis of forecasting is going far beyond the capacities of the present instruments. The data are, however, of the highest value in post-season studies, and undoubtedly a series of records over a period of years may prove of decided advantage in determining the relative difficulty of handling fires in the different seasons and in deciding whether any long-time fluctuations, as demanded by the sun-spot theory, have taken place.

SUMMARY

So far as California is concerned, on practically every day within the fire season from about June 10 to September 30 fires will start and spread. The most serious problem is encountered in the form of occasional days or short periods during which fires spread with extraordinary rapidity and control is difficult and costly. During such critical periods, which from 1920 to 1923 occurred not more than once or twice annually, a high percentage of the seasonal total of burned area piles up. For this region, therefore, the most important problem of prediction of fire weather is concerned with these short periods.

Analysis shows that these spells are characterized by very low relative humidity and by high wind velocity which are themselves the result of pressure distribution. Neither low relative humidity nor high wind velocity alone has resulted in such high rates of spread as the combination of the two factors.

The major fluctuations in the climatic factors within a fire season are generally simultaneous over most of the national forest region as well as the adjacent valleys in which the stations of the Weather Bureau are located. Reliable regional forecasts are of material value to the organizations attempting fire prevention and control. This is not, however, to imply that more localized forecasts and studies are not desirable, since obviously much remains to be done in this field.

The reliability of long-term forecasts is not yet demonstrated, as any generally favorable season, such as 1923, may have a short spell of adverse fire weather. Short-period forecasts, such as those made by the Weather Bureau, must be the chief reliance for the present.

Attempts to use rate of evaporation as a means of forecasting fire weather have been only partially successful. Rate of evaporation measures with fair reliability the fire danger and rate of spread, but it is not yet proved that forecasts can be made from these data, however valuable they may be in studying past events. Evaporation data can be used in localizing regional forecasts, but apparently should not be employed as the sole basis for predictions. Neither do the California data as to relative humidity point to any hope that local forecasts can be made from a study of this factor alone, important though it is. It may serve, like evaporation, in localizing regional forecasts.

In the California pine region short-term forecasts which will define the concurrence of low relative humidity and high winds will be most useful for administrative application. Such forecasts by the Weather Bureau, covering critical fire-control periods, offer a major opportunity for improving systematic fire protection in the pine region of California.

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